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A NEW METHOD TO MEASURE NEUTRINO OSCILLATIONS

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Thermonuclear Neutrinos

A New Method to Measure Neutrino Oscillations*

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Abstract

A method to measure possible neutrino oscillations of the disappearance type is described which is more sensitive, has smaller systematic uncertainty, and is of a fundamentally different class than any previous studies of this kind. The extremely intense neutrino sources that can be produced by capturing neutrons emitted from a thermonuclear explosive device can be tailored by choice of blanket material surrounding the device to yield a precisely known neutrino spectrum. These neutrinos can be observed at distances of 10km or more from the source, allowing neutrino mass differences as small as 10^{-4} eV^2 to be measured.

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Introduction

One of the most exciting developments in modern physics has been the success of gauge theories for the unification of electromagnetism and the weak nuclear force. Grand Unified models are attempts to extend this success to the strong nuclear interactions as well. An almost inevitable consequence of Grand Unification is the prediction of new rare processes such as proton decay and neutrino oscillations.

A necessary condition for the phenomena of neutrino oscillations is that at least one neutrino type have mass, and that the mass eigenstates ν_1, ν_2, ν_3, with masses m_1, m_2, and m_3, are not identical to the weak eigenstates ν_e, ν_μ, and ν_τ. For mixing between two neutrino types ν_1 and ν_2, the wavelength of the oscillation from one type, say ν_e , to another type, say ν_μ, is given by

$$\lambda = 2.5\ E_\nu / \Delta m^2 \tag{1}$$

where $\Delta m^2 = m_1{}^2 - m_2{}^2$ is in units of eV^2 and E_ν is in units of MeV.

With the mixing angle θ defined by

$$\nu_e = \nu_1 \cos\theta + \nu_2 \sin\theta \tag{2}$$

the number of electron neutrinos observed at a distance L, relative to the number produced at the origin is

$$N(L)/N(0) = 1 - 1/2 \sin^2 2\theta (1 - \cos 2.53\ \Delta m^2\ L/E_\nu) \tag{3}$$

Recently, it has been suggested[1] that the apparatus for proton decay experiments may be sensitive to very small neutrino mass differences by virtue of the difference of the earth's diameter in flight paths for atmospheric neutrinos reaching the detector from below as opposed to those arriving from above. However, the systematic uncertainties in the source distribution are great in this case, and only relatively large mixing angles may be probed. On even longer distance scales, the solar neutrino problem could conceivably be the result of complete mixing of electron neutrinos into three different species, but the solar models that predict the solar neutrino flux are not sufficiently convincing to prove this conclusively. If the solar neutrino problem[2)] is the result of neutrino oscillations, the oscillation length must be between 10^1 and 10^{11} m.

The most precise previous attempts to measure neutrino oscillations have been based on the electron anti-neutrinos emitted by the fission fragments produced in a nuclear reactor. Such experiments, however, suffer from very low counting rates, and relatively high systematic uncertainties. In fact, some early positive results[3)] for the existence of neutrino oscillations were later found to be due only to the systematic errors in the measurements. A typical reactor-based experiment[4)] requires a six month period in order to accumulate 10^4 neutrino events, and an additional month with the reactor off in order to measure the background rate. Although the statistical precision of this work is quite good, the systematic uncertainties in the fission generated neutrino spectrum are about 10% (95% confidence level), and dominate over the statistical error. Also, because of the inherently low flux of reactor neutrinos, such experiments are limited to distances on the order of tens of meters, and thus to values of Δm^2 on the order of 10^{-2} eV^2.

Thermonuclear Neutrinos

We describe in the following a method to observe low energy neutrinos (2 to 12 MeV) at distances of 10km or more, and consequently we can detect Δm^2 values as small as 10^{-4} eV^2. Our method is based on the unique characteristics of the neutrino flux which can be produced by a properly blanketed thermonuclear device. Although measurements of fission neutrinos from nuclear devices have been proposed in the past[5)], the much higher fluxes and neutrino energies that can be attained by utilizing the neutrons emitted from fusion devices have not been considered for the purpose of measuring neutrino mixing. One of the advantages of surrounding a fusion device with a suitably chosen blanket material is that we are able, through activation, to produce a large quantity of short-lived, high-energy beta emitters.

A particularly interesting example is boron carbide as the neutron absorbing material, since it is often included anyway as a blanket material to prevent ground activation. The capture of neutrons in B_4C produces, among other isotopes, the high energy beta-emitter, ^8Li (Q-value = 16.0005 MeV, $t_{1/2}$ = 844 ms) by the reaction

$$^{11}B + n \rightarrow {}^8Li + {}^4He \qquad (4)$$

with a reaction threshold of 6.63 MeV. A Monte Carlo calculation[6] for a one meter sphere of pure B_4C surrounding a 14.1 MeV neutron source predicts that 3.5% of the neutrons will undergo the above reaction (see Table 1). The antineutrino spectrum resulting from the beta decay of ^8Li is shown in Figure 1.

The antineutrinos can be detected via their reactions with the hydrogen atoms in a liquid organic scintillator

$$\bar{\nu}_e + p \rightarrow n + e^{+} \qquad : \qquad (5)$$

This reaction threshold is 1.8 MeV. Since the neutron recoil energy is small, the positrons receive most of the neutrino energy and deposit this energy promptly in the scintillator liquid. The neutrons may be detected by a delayed (0.2 ms) gamma ray of 2.2MeV following thermalization and capture in the hydrogen.

The advantage of producing high Q beta emitters such as ^{8}Li can be seen in figure 1, which compares the neutrino spectrum expected from the decay of ^{8}Li with the neutrino spectrum deduced from a measurement[7)] of betas from the fission of ^{239}Pu. Since the detection reaction cross section[8)] varies approximately quadratically for MeV energies,

$$\sigma_{\bar{\nu}+p\rightarrow n+e}(E_e) = \frac{2\pi^2 \hbar^3 \ln 2}{m_e^5 c^7 \, ft_{1/2}(n)} p_e E_e \qquad (6)$$

where $$E_e = E_\nu - 1.29 \text{ MeV} \qquad (7)$$

the ^{8}Li neutrinos have a considerably higher average cross section than fission neutrinos. Integrating the neutrino detection cross section with the ^{8}Li neutrino energy spectrum yields an average detection cross section of approximately 350 x $10^{-44}cm^2$, whereas the average cross section for the neutrinos from ^{239}Pu fission is approximately 40 x 10^{-44} cm^2 per fission decay (see Figure 2). For ^{235}U fission the average cross section is approximately 60 x 10^{-44} cm^2 per fission decay. Moreover, since the fission neutrinos come from a wide variety of different beta emitters, the time structure of the fission neutrino spectrum will be quite complicated due to the large number of fission fragments of widely varying Q-values and lifetimes that are produced in the fission process. Thus, fission neutrinos, both reactor based and those using fission explosives, would not only have a lower average energy and cross section, but also a much more complicated time-dependent structure. The reactor measurements, in contrast to our scheme, integrate the fission neutrino spectrum over long times, and thus see only the average neutrino flux spectrum shown in the figure. A primary advantage of the present scheme, therefore, is our detailed knowledge of the neutrino spectrum which can be tailored and dominated by a single isotope over large energy ranges, as well as our ability to stretch out the distance scale.

Figure 3 shows some typical results[7)] from various reactor experiments, and Figure 4 contrasts various accessible ranges of neutrino oscillation parameters. The hashed region in this plot corresponds to the range of parameters which can be explored by the present method. The limits of the hashed region are determined by the fusion yield of the nuclear device, (20kT was assumed for the present plot), the choice of B_4C as the target material, and the detector size. The number of neutrino events expected in the absence of oscillations would be about 10^4 at a distance from the source of 300m with a $400m^3$ volume of scintillator. The counting rate of these events would be determined by the 0.84s half life of ^8Li. To normalize the actual neutrino flux, at least two detectors would be needed, a "small" one at close distance, and a "large" one at long distance. The limits plotted can be extended even further to the dotted line by increasing the fusion yield, and by alternative blanket substances.

A significant background will be the approximately 10^4 cosmic ray events per second for a completely unshielded $400m^3$ detector (mostly penetrating muons). These events will have much larger energies than the neutrino events and can be rejected easily. This background will serve as a convenient monitor of the detector efficiency and energy calibration, since the energy of most of the muon events should simply be that for a minimum ionizing particle traversing the width of the individual detector modules. This illustrates another major advantage of the present scheme, in that the background is integrated over a time interval approximately 10^6 times shorter than that of the reactor experiments. As a result, much of the elaborate background rejection needed for reactor experiments is unneccesary, and the detector can be much simpler.

Summary

We have described an experiment to measure possible neutrino oscillations that is potentially two orders of magnitude more sensitive than reactor-based experiments. By utilizing the intense neutron fluxes that are emitted in the explosion testing of nuclear fusion devices, materials in a blanket surrounding the device can be activated to produce selected, short lived, high energy beta emitters resulting in a pulsed neutrino spectrum that is intense, unique, and well characterized. The reactor power normalizations and systematic uncertainties characteristic of fission neutrino measurements do not limit the precision or accuracy of the proposed measurements. In addition, our ability

to stretch out the distance scale to accommodate much longer wavelengths and to probe much smaller mixing angles, adds a new dimension to studies of possible neutrino oscillations.

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Table 1

High Energy Beta Emitters Produced by 14.1 MeV Neutrons Slowing Down in a 1 Meter Sphere in the Indicated Medium

Target	Reaction	Isotope	End-Point Energy (MeV)	Half-Life	Fraction of Neutrons Absorbed
In pure B_4C:					
^{11}B	(n,α)	^{8}Li	13.1	0.84 s	3.5%
^{11}B	(n,p)	^{11}Be	11.5	13.8 s	0.4%
^{12}C	(n,p)	^{12}B	13.4	0.02 s	0.03%
In pure NaF:					
^{19}F	(n,α)	^{16}N	10.42	7.13 s	3.8%
^{19}F	(n,γ)	^{20}F	7.03	11.0 s	1.0%
^{23}Na	(n,α)	^{20}F	7.03	11.0 s	8.4%
In pure NaCl:					
^{23}Na	(n,α)	^{20}F	7.03	11.0 s	7.23%
^{23}Na	(n,p)	^{23}Ne	4.38	37.6 s	2.74%
^{23}Na	(n,γ)	^{24}Na	5.51	15 hours	1.0%

FIGURE CAPTIONS

Fig. 1 Antineutrino spectrum resulting from the decay,

$$^{8}Li \rightarrow {}^{8}Be + e^{-} + \bar{\nu}_e$$

contrasted with the spectrum from fission decays.

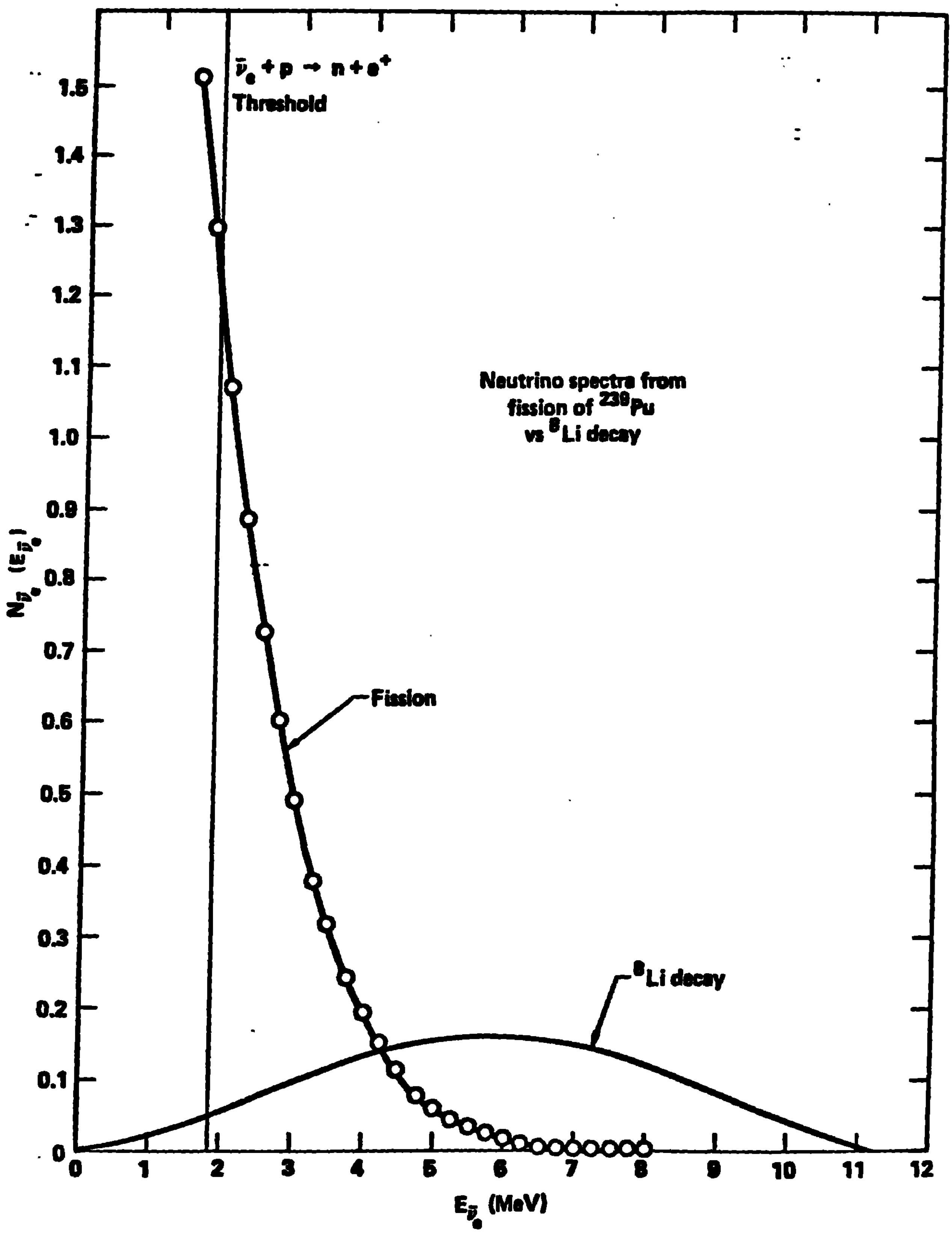
Fig. 2 Positron energy spectra resulting from either neutrinos emitted by ^{8}Li decay or by the various fragments following ^{239}Pu fission, plotted as a function of neutrino incident energy.

Fig. 3 Measured e^{+} yields measured at a distance L from the ILL and Gosgen reactors (normalized to the corresponding $\bar{\nu}_e$ source spectra) are compared with expected yields and approximate uncertainties for the present experiment at a distance of 500m.

Fig. 4 Curves of the oscillation parameter $\Delta m^2 = m_1{}^2 - m_2{}^2$ vs. $\sin^2 2\theta$ are plotted for several experiments. In each case, the regions to the right of the curve can be excluded.

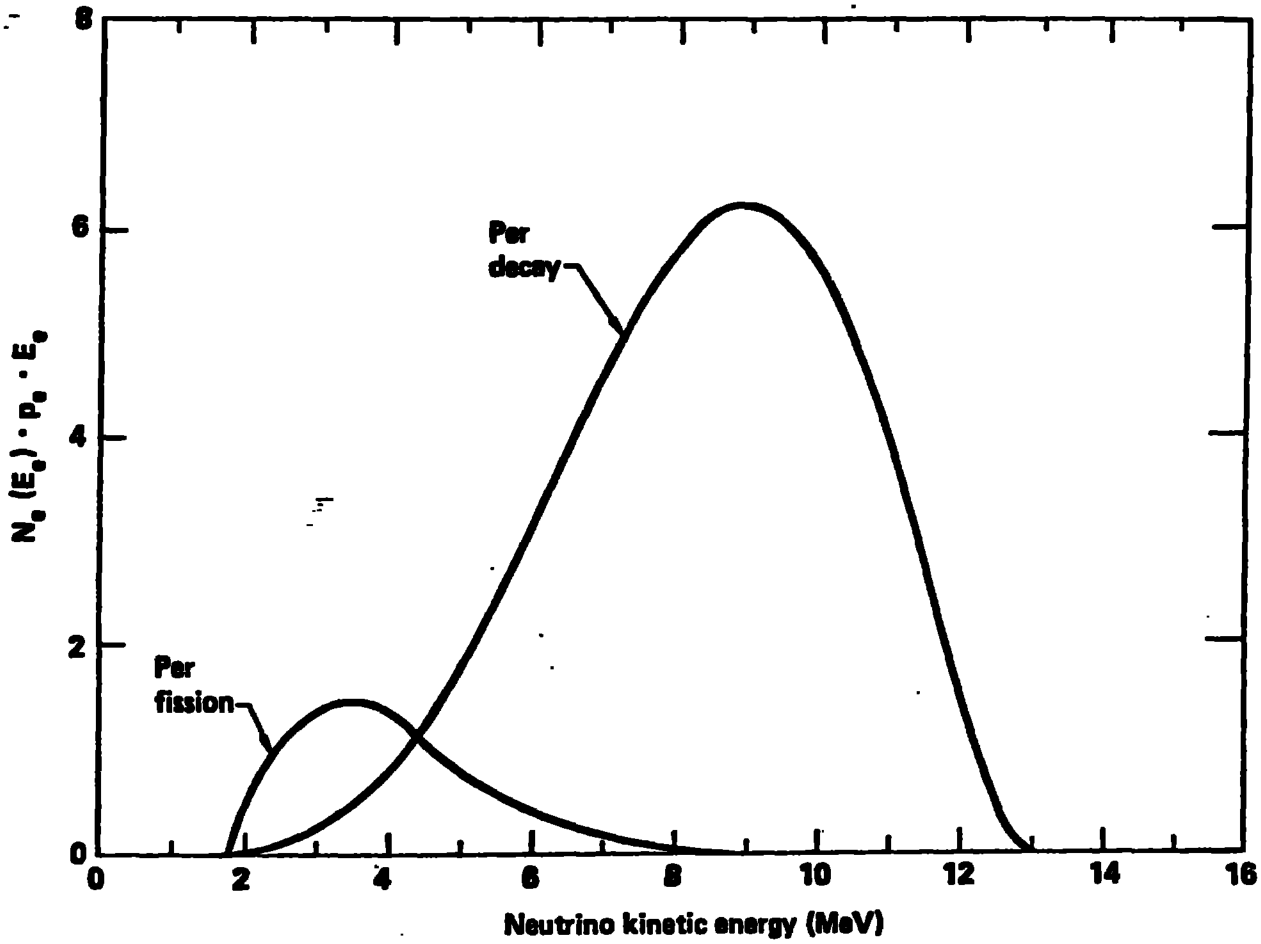
(a) L = 8.8m, (b) L = 38m, the cross hatched region is the present arrangement, ultimately extendable to the lower dotted curve.

FIGURE 1



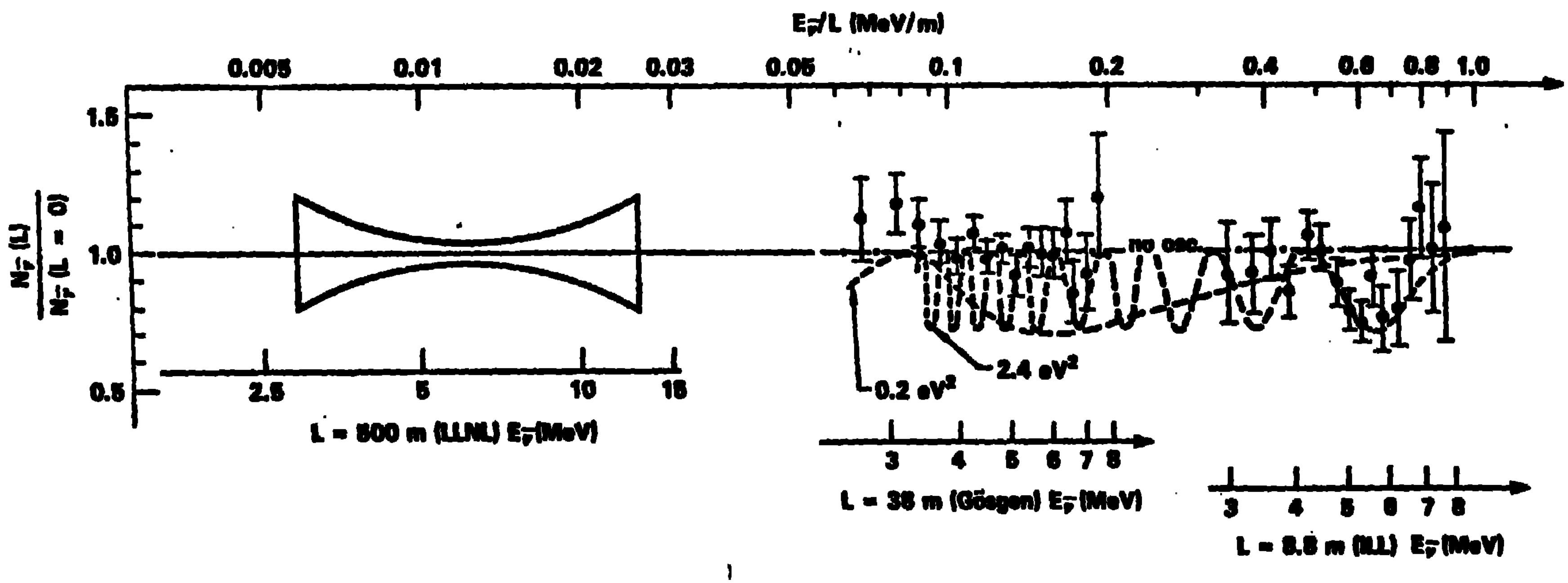
$\bar{\nu}_e + p \rightarrow n + e^+$
Threshold
Neutrino spectra from fission of ^{239}Pu vs ^{8}Li decay
Fission
^{8}Li decay
$N_{\bar{\nu}_e}(E_{\bar{\nu}_e})$
$E_{\bar{\nu}_e}$ (MeV)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
0
1
2
3
4
5
6
7
8
9
10
11
12

FIGURE 2



Per decay
Per fission
$N_e(E_e) \cdot p_e \cdot E_e$
Neutrino kinetic energy (MeV)
0
2
4
6
8
0
2
4
6
8
10
12
14
16

FIGURE 3



$E_{\bar{\nu}}/L$ (MeV/m)
0.005
0.01
0.02
0.03
0.05
0.1
0.2
0.4
0.6
0.8
1.0
1.5
1.0
0.5
$\frac{N_{\bar{\nu}}(L)}{N_{\bar{\nu}}(L=0)}$
no osc.
2.4 eV²
0.2 eV²
2.5
5
10
15
L = 500 m (LLNL) $E_{\bar{\nu}}$(MeV)
3
4
5
6
7
8
L = 38 m (Gösgen) $E_{\bar{\nu}}$(MeV)
3
4
5
6
7
8
L = 8.8 m (ILL) $E_{\bar{\nu}}$(MeV)

FIGURE 4